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Comparison of Permanent Magnet Synchronous and Induction Generator for a Tidal Current Conversion System with Onshore Converters

Marios C. Sousounis*, Jonathan K.H. Shek, Richard C. Crozier, Markus A. Mueller
Institute for Energy Systems, School of Engineering
The University of Edinburgh, The King's Buildings, Mayfield Road
Edinburgh, EH9 3JL, United Kingdom
*M.Sousounis@ed.ac.uk

***Abstract*—Tidal current conversion systems are moving towards commercialisation. Tidal energy developers are looking to optimise their systems by testing all the available options and taking advantage of the experience from the wind energy industry. The key focus of this paper is to compare an induction generator with a permanent magnet synchronous generator in a tidal current conversion system with onshore converters. The architecture of a tidal system with onshore converters is an option for tidal sites with small distances to shore as previous research has shown. In order to investigate the two generator technologies full resource-to-grid models in MATLAB/Simulink are developed. The analysis of these models compares generator efficiency, energy capture, losses at each stage, the cost and the maintenance for each system. Results show that the tidal system with PMSG is more efficient and generates fewer losses to transmit power onshore. In addition, since both systems tested are using a gearbox, the size, cost and maintenance of the PMSG are comparable to the reliable and cost-effective option of SCIG.**

Keywords— tidal energy conversion; marine energy; variable speed drives; induction generator; permanent magnet synchronous generator

I. INTRODUCTION

The commercial deployment of tidal current conversion systems (TCCS) is closer compared to other technologies that harvest marine hydrokinetic (MHK) energy [1, 2]. The tidal current energy resource which can be extracted with today's tidal current turbines is significant and can supply 29% of the UK electricity demand based on 2013 statistics [3]. Even though TCCS have similarities to offshore wind systems in many aspects, some differences such as predetermined available area in a tidal channel, continuous underwater operation and smaller distances to shore change the optimum approach for energy transmission and drivetrain design [4].

The TCCS require continuous underwater operation if they are going to become cost competitive. Downtime must be reduced to minimum by using reliable components offshore and keeping system availability as high as possible. This also dictates that onsite visits must be reduced to a minimum since tidal devices are usually installed at locations with strong tidal currents. At these locations, the windows of opportunity for onsite visits are relatively short (often less than one hour), which means that major operations need to be extremely quick or be able to continue in high flow speeds [4].

In addition to the above, offshore substations and high-voltage subsea transmission can be avoided in tidal arrays due to the fact that tidal resource is usually close to shore. Taking advantage of the above, tidal energy developers can extend the availability of their systems by moving the power electronics from the nacelle to the shore. Reducing the components that are installed offshore can consequently increase the availability of the TCCS. Power electronics' failure frequency is significant and if they are placed offshore downtime of a failure will increase. Locating the power electronics on land means that the generator has to be controlled using long subsea cables and therefore long distance drives are needed. Long distance converters have been used to drive electrical submersible pumps (ESPs) in oil offshore platforms.

The literature regarding long distance drives focuses on the variable speed operation of low power motors which are usually designed to be used as pumps in offshore oil platforms [5 - 7] or mines [8]. The main points discussed are the reasons behind the appearance of over-voltages at the terminals of motors with long feeders [5], filtering techniques in order to mitigate the problems associated with the long feeders [5, 6], and the importance of accurate frequency domain analysis in order to investigate system resonant frequency in different topologies [7, 8]. In [6] authors also discuss the effect of long cables in a PWM vector controller.

Currently, tidal current turbine developers have not yet decided on the optimal TCCS and therefore a number of different designs exist. While most of the designs are bottom mounted with low solidity blades and horizontal axis rotors, the approaches differ in generator technology. Authors in [9] summarise the advantages and disadvantages of the different generator options for TCCS. They also present results when a permanent magnet synchronous generator (PMSG) is compared with a DFIG. The authors conclude that a direct drive (DD) PMSG is the optimum choice for TCCS because of the higher amount of harnessed energy and lower maintenance. In [10] authors with industrial experience analyse different

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tidal array formations based on lower cost and maintenance requirements. They conclude that their preferred option is a wound field synchronous generator (WFSG) with DC transmission and their second option would be a squirrel cage induction generator (SCIG), PMSG or WFSG with long distance controls which are referred as variable frequency collection option in the paper. In most papers that appear in the literature regarding TCCS authors consider the design [11, 12] and operation [13 - 15] of PMSGs with or without gearbox. In addition, authors in [16] study the effects of onshore converters in a TCCS with a PMSG.

The aim of this paper is to compare a geared SCIG and a geared PMSG in a full resource-to-grid TCCS with onshore converters. The system was first presented in [17] and is based on a three-bladed tidal turbine with pitch-regulated blades and a SCIG controlled using direct torque control (DTC) with space vector modulation (SVM). Utilising the dynamic model, we compare the operation of the TCCS in regard to losses generated at each part of the system, cost, maintenance and total energy captured from the tides. Section 2 briefly explains the modeling of the tidal resource, cables, tidal turbine power characteristics, and the generator and grid side controllers. Section 3 shows the results from the simulation of the model and comparisons are drawn based on specific criteria. Conclusions are presented at the end of this paper.

II. MODELING THE TIDAL CURRENT CONVERSION SYSTEM

In this section the modelling aspects of a tidal current conversion system will be described. The generalized topology of the TCCS can be seen in Fig. 1.

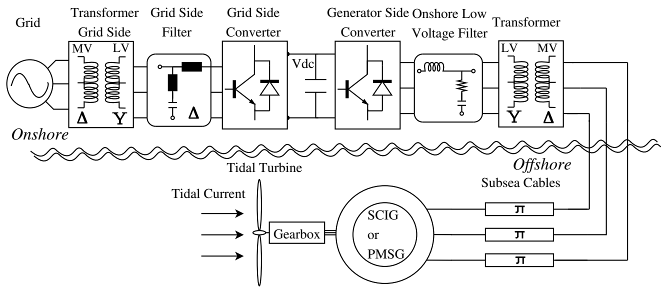

Fig. 1. The generalized topology of the tidal current conversion system with onshore converters.

The system topology with onshore converters was first presented in [17] and was based on a three-bladed tidal turbine with pitch-regulated blades and a SCIG controlled using DTC SVM. In this paper we present a generalized topology in order to be able to draw fair comparisons between the PMSG and the SCIG. This means that the majority of the components remain the same and only the generator and the generator side controller are different.

In the generalized topology the tidal turbine shaft is connected to the generator rotor through a gearbox. In both cases, the PMSG and the SCIG, the same gearbox ratio is used. The output of the medium voltage generator is transmitted to shore by long three-phase subsea cables. The medium voltage is transformed to low voltage using an onshore transformer. Before the generator side voltage source converter (VSC) filters are installed to mitigate harmonics and over-voltages. The generator side controller enables variable speed operation of the generator and therefore maximum power capture from the tides. On the grid side, the low voltage output of the inverter is first filtered and then a step-up transformer is used in order to match the high voltage at the grid.

In the following subsections the tidal resource, the generator controller for each case and cable modelling are presented. The grid side controller, the tidal turbine characteristics and the pitch controller are described in detail in [17].

A. *Tidal resource*

The power potential of tidal currents can be derived by the same formula as for wind energy systems.

$$P_{tide} = 0.5 \cdot \rho_{water} \cdot A \cdot V_{current}^3 \tag{1}$$

Where ρ_{water} is the sea water density approximately equal to $1025\text{kg}\cdot\text{m}^{-3}$, A is the swept area by the tidal turbine blades and $V_{current}$ is the fluid speed in m/s.

As input to the model a half tidal period of a semidiurnal high tide with high peak flow speed was chosen in order to represent the most complex period of operation of the system. The tidal current speed used is shown in Fig. 2 which was derived from measured data.

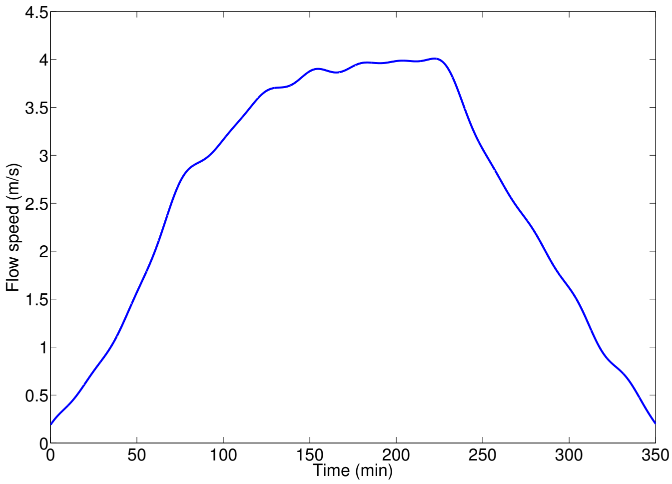

Fig. 2. Tidal current speed used as input to the system

B. *Cable modeling*

The subsea cables have been modelled using a number of series connected π-sections in order to accurately represent the uniform distribution of parameters along the cables for a wide frequency range. The parameters for the subsea cables are given in Table I.

TABLE I. SUBSEA CABLE PARAMETERS

Quantity	*Value*
Cable resistance per unit length	0.1970 Ω/km
Cable inductance per unit length	0.742 mH/km
Cable Capacitance per unit length	0.31 μF/km
Cable length	3.5 km
Number of π-sections	3

C. *Generator controllers*

1) *Direct Torque Control with Space Vector Modulation*

The variable speed operation of the TCCS with a SCIG is achieved by using the DTC SVM scheme with closed loop torque and flux control in stator flux coordinates. The DTC SVM scheme implemented is based on the classical DTC but also operates at constant switching frequency. The control structure of the DTC SVM modelled can be seen in Fig. 3.

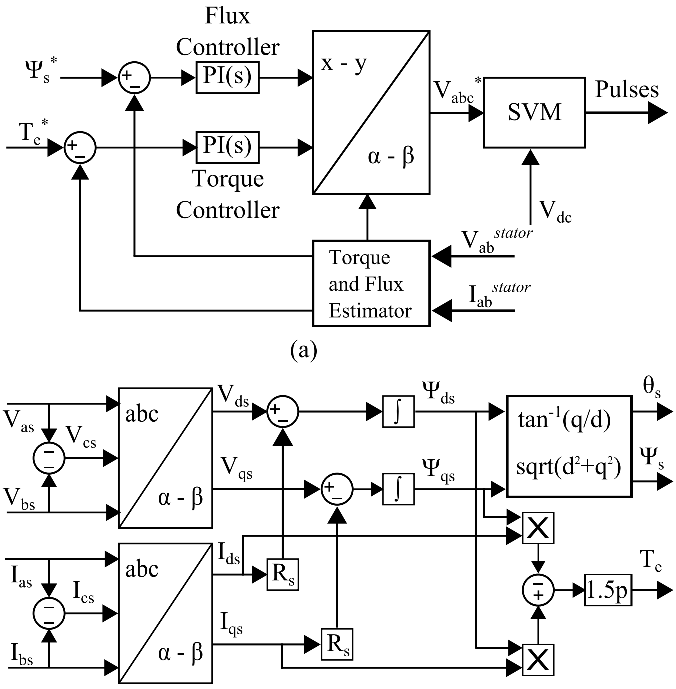

Fig. 3. Block diagram of the DTC SVM method used to control the SCIG. (a) DTC SVM method with closed-loop torque and flux control in stator flux coordinates. (b) Torque and Flux estimator.

Where R_s is stator resistance, p is the number of pole pairs, Ψ denotes magnetic flux, θ denotes angle and T_e is the electromagnetic torque. More details regarding the SVM method are given in [17 – 18].

2) *ZDC SVM*

The DTC SVM method described above is used to control the SCIG. In order to ensure variable speed operation of the PMSG the zero d-axis current control with space vector modulation (ZDC SVM) has been implemented. The block diagram of the controller can be seen in Fig. 4.

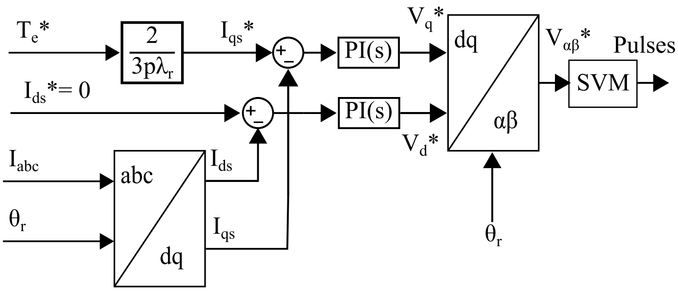

Fig. 4. Block diagram of the ZDC SVM method used to control the PMSG.

Where λ_r is the flux induced by the magnets of the rotor.

III. Simulation Results and Comparison

In the literature generators are compared based on efficiency, cost and weight. In [9] the authors additionally focused in the variable speed operation of their system and the range of tidal speeds the generator can produce energy. The additional comparison criterion proposed in [9] is less important in this research paper because both generators use fully rated back-to-back (BTB) converters and therefore the generators have no operating speed restrictions. This is not the case for the doubly fed induction generator (DFIG) presented in [9] that uses 25% of the full rating of the generator which imposes speed restrictions. A DFIG generator was not considered in this research paper because, due to the unique electrical architecture with the onshore converters, two long three phase cables would be required to transmit power. The first three phase cable would be directly connected to the grid and the second three phase cable would be connected to the BTB converters. This is considered uneconomical as it will double the cost of cables required.

The criteria we selected to compare a TCCS with onshore converters using a SCIG and an identical one using a PMSG are cost and maintenance, generator efficiency at different operating speeds and losses generated for the power to be transmitted to shore. The criterion of losses for power transmission is important for this specific electrical topology as it will be revealed in the following sections.

A. *Cost and maintenance*

First of all identical components are excluded from the comparison. These components include the gearbox and the power electronics. Also, it should be noted that both generator types are brushless.

The SCIG is a proven technology as the industry relies on that type of generator for many applications for many decades. For these reasons the SCIG is an economical solution for a generator with low maintenance requirements, high reliability and low weight.

The PMSG uses permanent magnets whose cost varies but in general are expensive compared to the straight forward design of the SCIG. In this paper we use a geared PMSG and therefore number of pole pairs, size, cost and structural mass are comparable to the SCIG. Based on research for wind turbines the cost and weight of PMSG can be the same or even cheaper compared to an induction generator [19].

B. *Generator efficiency and energy capture*

The second criterion to compare the TCCS with SCIG and PMSG is to calculate the generator efficiency. Equations (2), (3) and (4) describe the process to calculate generator efficiency.

$$P_{input}(\mathrm{W}) = T_{mechanical} \cdot \omega_{mechanical} \tag{2}$$

$$P_{electrical}(\mathrm{W}) = I_a \cdot V_a + I_b \cdot V_b + I_c \cdot V_c \tag{3}$$

$$\eta(\%) = (P_{electrical}/P_{input}) \cdot 100 \tag{4}$$

Where P_{input} is the mechanical power input to the generator, $P_{electrical}$ is the electrical power output of the generator and η is the efficiency. Fig. 5a shows the efficiency of the SCIG and the PMSG during the operation of the TCCS and Fig. 5b depicts the efficiency of each system versus the power output of the generator in per unit.

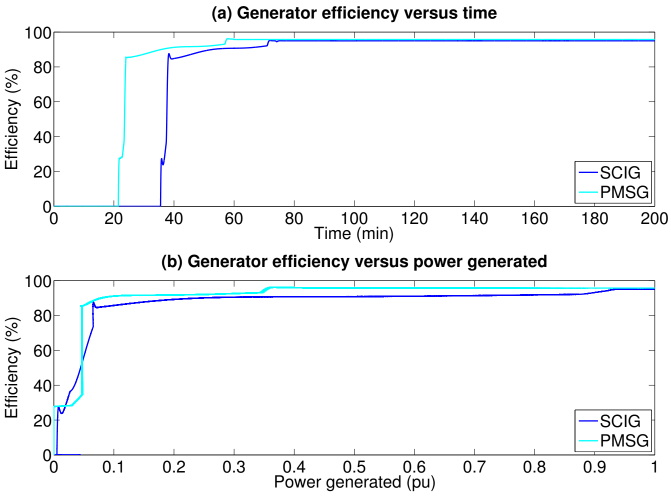

Fig. 5. (a) Generator efficiency comparison during operation (b) Generator efficiency comparison versus power generated.

We can observe that the PMSG starts to generate power 14 minutes earlier compared to the SCIG. At that time the tidal flow speed is low, less than 0.8m/s, and therefore the power generated is low. The additional power the PMSG extracts from the tides during the 14minutes for a 1MW TCCS is estimated to be 7kWh.

As a general observation it can be said that the PMSG has higher efficiency compared to the SCIG at all operating points. When the systems operate at rated power efficiency difference between the PMSG and the SCIG is 0.5%.

In order to calculate the energy capture the histogram of the tidal speed is required. Fig.6 depicts the histogram for a year of the tidal speed used as input to the TCCS modeled.

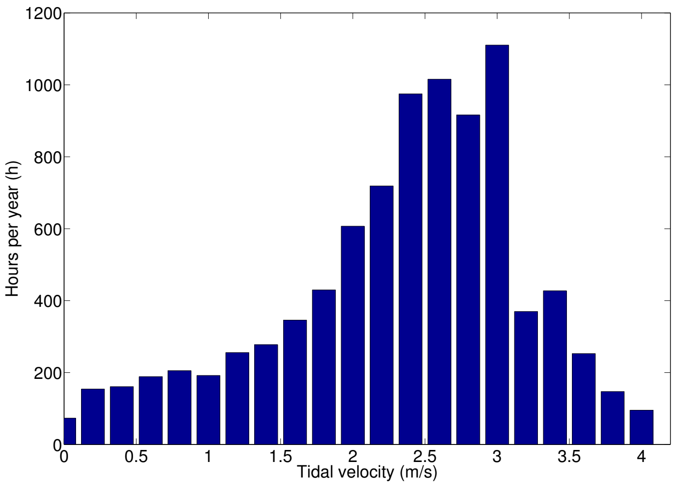

Fig. 6. Tidal histogram for a year. The bins of the histogram are 0.2 m/s wide.

The power generated from the SCIG and PMSG based TCCS is shown in Fig. 7. Combining Fig. 6 and Fig. 7 the total energy capture per year for each system can be calculated. Fig. 8 depicts the captured MWh per year for each tidal speed bin for a 1MW TCCS.

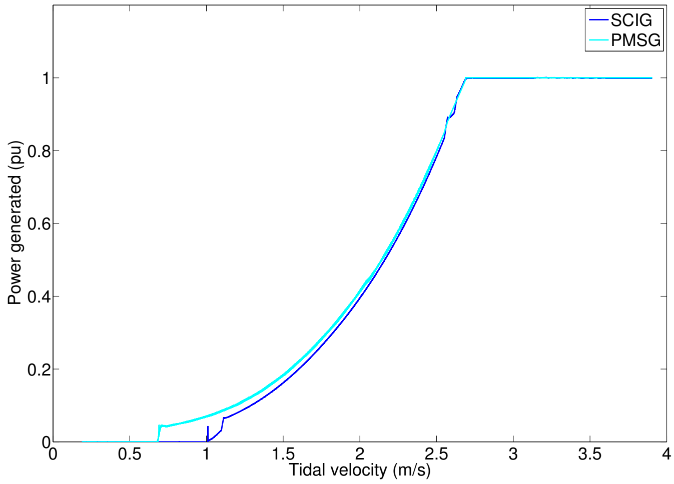

Fig. 7. Comparison of power generated in pu versus tidal flow speed between the SCIG and PMSG.

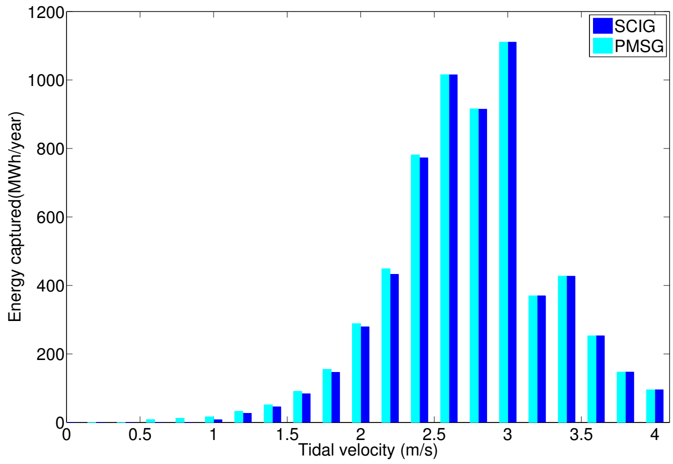

Fig. 8. Comparison of energy captured in MWh/year versus tidal flow speed between the SCIG and PMSG for a 1MW TCCS.

In Fig. 7 it is evident that the TCCS that uses PMSG starts generating power at lower tidal speeds compared to the TCCS that uses SCIG. For tidal speeds above 2.7 m/s both systems generate rated power. The above trend has an impact on the energy capture in each case. As it is observed in Fig. 8 at tidal speeds below 2.7 m/s the PMSG case captures more energy compares to the SCIG case. At tidal speeds above 2.7 m/s the energy capture is almost similar for both cases. The total yearly captured energy for the SCIG case is 6127MWh and for the PMSG case is 6222MWh. Therefore, by using a PMSG an additional 95MWh can be captured per year for a 1MW device. However, the change in generator technology and control method can also have an effect on the losses that appear in the system and therefore change the overall efficiency of the system. This is the reason why at the next section an overview of system losses is given.

C. Losses at each stage of the system

Studying and comparing the losses between the generator and the onshore converter is of extreme importance for a TCCS that uses long distance controls. These losses also include the transmission losses of the system and can affect significantly the total power exported to the grid. In both TCCS under consideration, three components are connected between the generator and the onshore VSC. These components are the long three phase cables, the transformer and a low voltage filter. Table II summarises the results regarding the losses under different operating stages of the system. The grid side losses include DC link losses, grid filter losses and grid transformer losses.

Observing the two generator cases separately we can note that cable and transformer losses are increasing as the power generated is increasing. This is due to the increased current that is generated as more power is produced. As the current increases more power is dissipated at the resistances of the transformer and the cable. On the other hand filter losses are decreasing as the power generated is increasing. The reason behind this trend is the fact that the filter has significant constant losses and therefore when these losses are calculated as a percentage to power generated they decrease.

TABLE II. POWER LOSSES AT EACH COMPONENT

Power generated (pu)	*Component*	*Losses (% of power generated)*		
		SCIG	*PMSG*	*Difference*
1.00	Cables	2.105	1.859	0.246
	Transformer	1.123	1.012	0.111
	Filter	0.288	0.248	0.040
	Grid side	4.725	4.685	0.040
0.75	Cables	1.885	1.537	0.348
	Transformer	0.914	0.853	0.061
	Filter	0.323	0.298	0.025
	Grid side	4.832	4.775	0.057
0.50	Cables	1.585	1.263	0.322
	Transformer	0.791	0.723	0.068
	Filter	0.666	0.581	0.085
	Grid side	4.735	4.715	0.020
0.25	Cables	1.257	1.056	0.201
	Transformer	0.598	0.481	0.117
	Filter	1.261	0.932	0.329
	Grid side	6.263	6.185	0.078

Comparing the losses generated between the TCCS using the SCIG and the PMSG it can be seen that there is a significant difference in cables and filter losses and a less significant change in transformer losses. The TCCS with the SCIG has approximately 0.35% more losses compared to the system with the PMSG. In order to investigate and justify the reasons behind this difference currents and voltages at the output of the generator for each case are depicted in Fig. 9.

As it is depicted in Fig. 9 generator voltages and currents from both cases are close to 1pu during operation at rated power as it is expected. The voltage total harmonic distortion (VTHD) for the SCIG and PMSG are 13.62% and 6.21% respectively while the current THD is 2.4% and 0.4% respectively. The additional harmonics that are present in the SCIG case generate extra power losses in the TCCS.

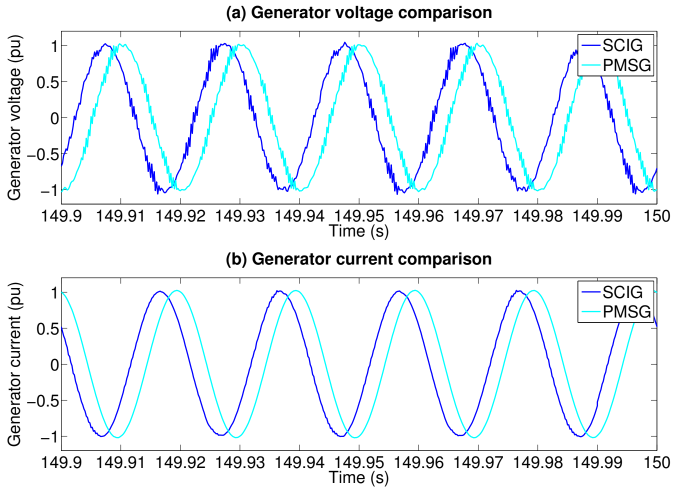

Fig. 9. (a) Generator voltage comparison (b) Generator current comparison.

Having calculated the total system losses the overall electrical efficiency of the TCCS can be calculated for each case and each operating point. Using the calculated overall efficiency the total exported energy to the grid can be calculated by utilising the results from Fig. 8. The yearly energy exported to the grid for each case is depicted in Fig. 10 for different tidal velocity bins.

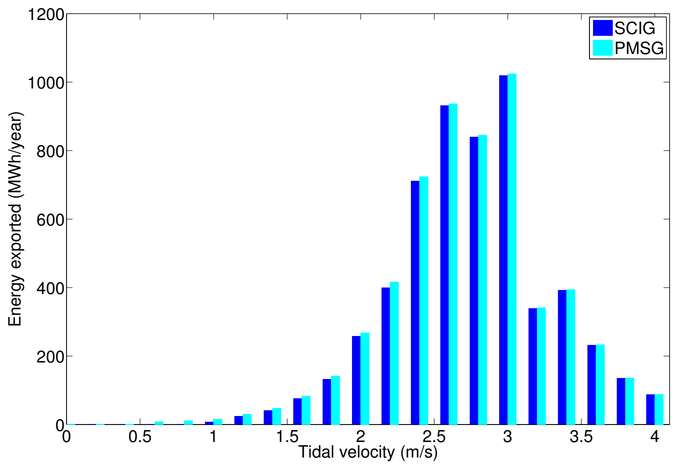

Fig. 10. Comparison of energy exported to the grid for the SCIG and PMSG based TCCS. The calculations are based on a 1MW tidal turbine.

The total yearly exported energy for the SCIG case is 5624MWh and for the PMSG case is 5740MWh. Therefore, by using a PMSG an additional 116MWh can be exported to the grid per year for a 1MW device.

IV. CONCLUSION

In this paper a PMSG and a SCIG are compared in a TCCS with onshore converters in a simulation research. The TCCS modelled is based on previous research and therefore modelling focus was given in generator controller structures for SCIG and PMSG. The comparative study concentrated on the cost and maintenance of each generator, the efficiency, energy capture and transmission losses. Based on results presented regarding efficiency, the PMSG produced more power throughout the half tidal period of a semidiurnal tide. In addition to this, the PMSG is advantageous when the electrical topology is using onshore converters. As simulation results showed, the TCCS that uses SCIG has more total system losses compared to the TCCS with a PMSG. Overall the PMSG seems a more interesting option from the electrical point of view for a TCCS with onshore converters. Future research will focus on direct drive generators and transmission cable study.

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